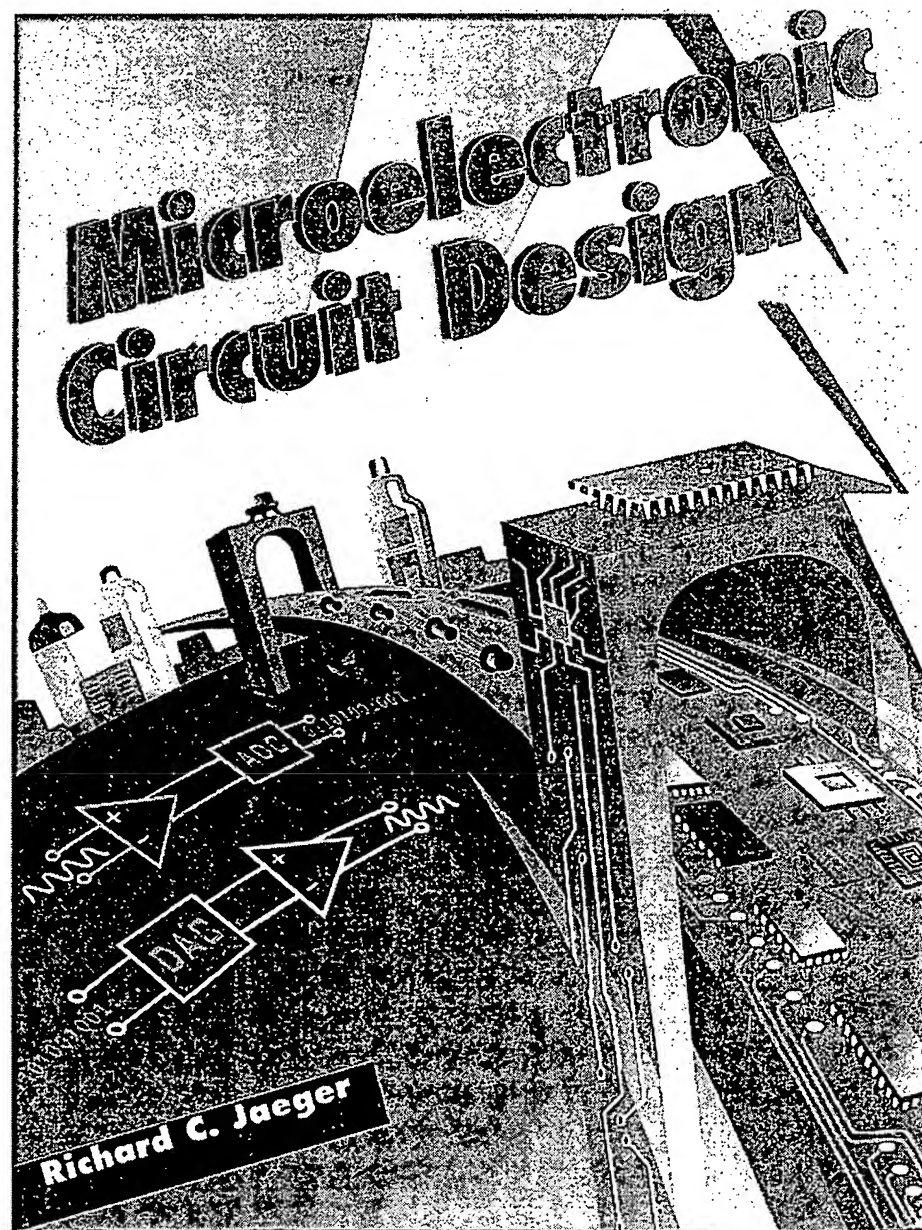


EXHIBIT A



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**MICROELECTRONIC CIRCUIT DESIGN**

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The evolution of solid-state materials and the subsequent development of the technology for integrated circuit fabrication have revolutionized electronics. Using silicon as well as other crystalline semiconductor materials, we can now fabricate integrated circuits (ICs) that have hundreds of millions of electronic components on a single  $2\text{ cm} \times 2\text{ cm}$  die. Most of us have some familiarity with the very high-speed microprocessor and memory components that form the building blocks for personal computers and workstations. As this edition is being written, technology for the 1-gigabit (Gb) memory chip is being developed in a number of research laboratories around the world. The memory array alone on this chip will contain more than  $10^9$  transistors and  $10^9$  capacitors—more than 2 billion electronic components on a single die!

Our ability to build such phenomenal electronic system components is based on a detailed understanding of solid-state physics as well as on development of fabrication processes necessary to turn the theory into a manufacturable reality. Integrated circuit manufacturing is an excellent example of a process requiring a broad understanding of many disciplines. IC fabrication requires knowledge of physics, chemistry, electrical engineering, mechanical engineering, materials engineering, and metallurgy, to mention just a few disciplines. The breadth of understanding required is a challenge, but it makes the field of solid-state electronics an extremely exciting and vibrant area of specialization.

The material in this chapter provides the background necessary for understanding the behavior of the solid-state devices presented in subsequent chapters. We begin our study of solid-state electronics by exploring the characteristics of crystalline materials, with an emphasis on silicon, the most commercially important semiconductor. We look at electrical conductivity and resistivity and discuss the mechanisms of electronic conduction. The technique of impurity doping is discussed, along with its use in controlling conductivity and resistivity type.

**Table 2.1**  
**Electrical Classification**  
**of Solid Materials**

Materials	Resistivity ( $\Omega \cdot \text{cm}$ )
Insulators	$10^5 < \rho$
Semi-conductors	$10^{-3} < \rho$ $< 10^5$
Conductors	$\rho < 10^{-3}$

## 2.1 SOLID-STATE ELECTRONIC MATERIALS

Electronic materials generally can be divided into three categories: insulators, conductors, and semiconductors. The primary parameter used to distinguish among these materials is the resistivity  $\rho$ , with units of  $\Omega \cdot \text{cm}$ . As indicated in Table 2.1, insulators have resistivities greater than  $10^5 \Omega \cdot \text{cm}$ , whereas conductors have resistivities below  $10^{-3} \Omega \cdot \text{cm}$ . For example, diamond, one of the highest quality insulators, has a very large resistivity,  $10^{16} \Omega \cdot \text{cm}$ . On the other hand, pure copper, a good conductor, has a resistivity of only  $3 \times 10^{-6} \Omega \cdot \text{cm}$ . Semiconductors occupy the full range of resistivities between the insulator and conductor boundaries; moreover, the resistivity can be controlled by adding various impurity atoms to the semiconductor crystal.

Elemental semiconductors are formed from a single type of atom (column IV of the periodic table of elements; see Table 2.2), whereas compound semiconductors can be formed from combinations of elements from columns III and V or columns II and VI. These latter materials are often referred to as III-V (3-5) or II-VI (2-6) compound semiconductors. Table 2.3 presents some of the most useful possibilities. There are also ternary materials such as mercury cadmium telluride, gallium aluminum arsenide, gallium indium arsenide, and gallium indium phosphide.

Historically, germanium was one of the first semiconductors to be used. However, it was rapidly supplanted by silicon, which today is the most important semiconductor material. Silicon has a wider bandgap energy,<sup>1</sup> allowing it to be used in higher-temperature applications than germanium, and oxidation forms a stable insulating oxide on silicon,

<sup>1</sup> The meaning of bandgap energy is discussed in detail in Secs. 2.3 and 2.8.



where  $Q$  = charge density  
 $v$  = velocity of charge in electric field

In order to find the charge density, we explore the structure of silicon using both the covalent bond model and (later) the energy band model for semiconductors. We relate the velocity of the charge carriers to the applied electric field in Sec. 2.4.

### 2.3 COVALENT BOND MODEL

Atoms can bond together in amorphous, polycrystalline, or single-crystal forms. Amorphous materials have a totally disordered structure, whereas polycrystalline material consists of a large number of small crystallites. Most of the highly useful properties of semiconductors, however, occur in high-purity, single-crystal material. Silicon—column IV in the periodic table—has four electrons in the outer shell. Single-crystal material is formed by the covalent bonding of each silicon atom with its four nearest neighbors in a highly regular three-dimensional array of atoms, as shown in Fig. 2.1. Much of the behavior we discuss can be visualized using the simplified two-dimensional covalent bond model of Fig. 2.2.

At temperatures approaching absolute zero, all the electrons reside in the covalent bonds shared between the atoms in the array, with no electrons free for conduction. The outer shells of the silicon atoms are full, and the material behaves as an insulator. As the temperature increases, thermal energy is added to the crystal and some bonds break, freeing a small number of electrons for conduction, as in Fig. 2.3. The density of these free electrons is equal to the intrinsic carrier density  $n_i$  ( $\text{cm}^{-3}$ ), which is determined by material properties and temperature:

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad \text{cm}^{-6} \quad (2.2)$$

where  $E_G$  = semiconductor bandgap energy in eV (electron volts)

$k$  = Boltzmann's constant,  $8.62 \times 10^{-5}$  eV/K

$T$  = absolute temperature, K

$B$  = material-dependent parameter,  $1.08 \times 10^{31}$   $\text{K}^{-3} \cdot \text{cm}^{-6}$  for Si

INTRINSIC  
CARRIER  
DENSITY

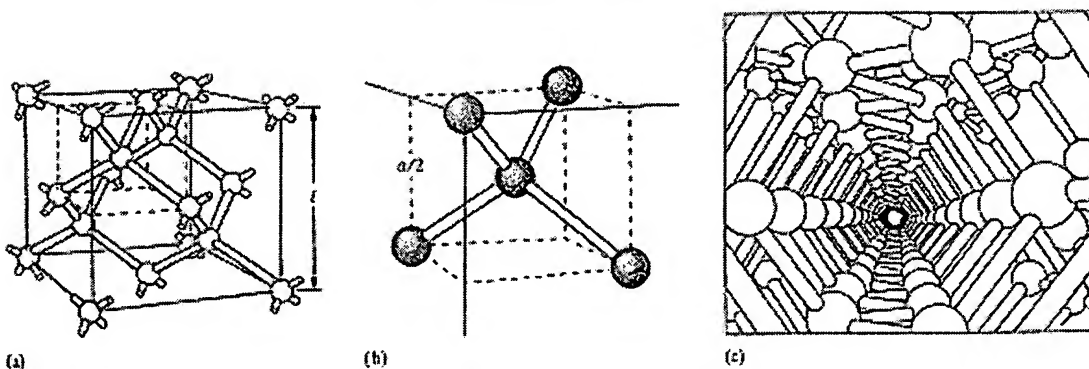


Figure 2.1 Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length  $l = 0.543$  nm. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis. [(a) and (b) adapted from *Electrons and Holes in Semiconductors* by William Shockley, © 1950 by Litton Educational Publishing. (c) adapted from *The Architecture of Molecules* by Linus Pauling and Roger Hayward, copyright © 1964 by W. H. Freeman and Company, used with permission; and *Semiconductor Devices: Physics and Technology* by S. M. Sze, copyright © 1985 by Bell Telephone Laboratories, by permission of John Wiley & Sons, Inc.]

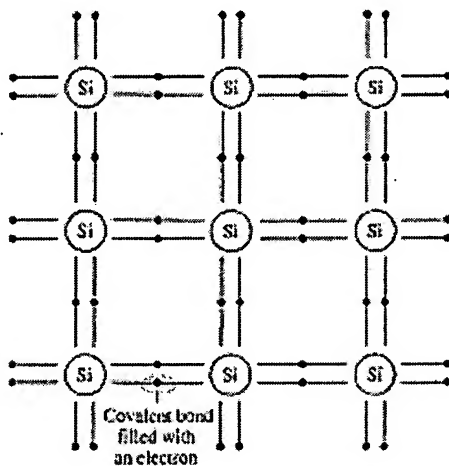


Figure 2.2 Two-dimensional silicon lattice with shared covalent bonds. At temperatures approaching 0 K, all bonds are filled, and the outer shells of the silicon atoms are completely full.

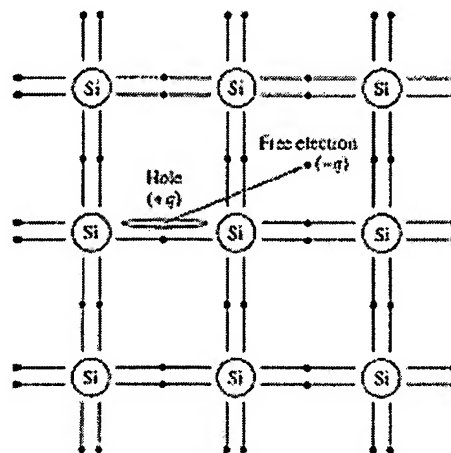


Figure 2.3 An electron-hole pair is generated whenever a covalent bond is broken.

Bandgap energy  $E_G$  is the minimum energy needed to break a covalent bond in the semiconductor crystal, thus freeing electrons for conduction. Table 2.3 lists values of the bandgap energy for various semiconductors.

The *density of conduction (or free) electrons* is represented by the symbol  $n$  (electrons/cm<sup>3</sup>), and for *intrinsic material*  $n = n_i$ . The term *intrinsic* refers to the generic properties of pure material. Although  $n_i$  is an intrinsic property of each semiconductor, it is extremely temperature-dependent for all materials. Figure 2.4 has examples of the strong variation of intrinsic carrier density with temperature for germanium, silicon, and gallium arsenide.

**EXAMPLE 2.1:** As an example, let us calculate the value of  $n_i$  in silicon at room temperature (300 K):

$$n_i^2 = 1.08 \times 10^{31} (\text{K}^{-3} \cdot \text{cm}^{-6}) (300 \text{ K})^3 \exp \left( \frac{-1.12}{(8.62 \times 10^{-5} \text{ eV/K})(300 \text{ K})} \right)$$

$$n_i^2 = 4.52 \times 10^{19} / \text{cm}^6 \quad \text{or} \quad n_i = 6.73 \times 10^9 / \text{cm}^3$$

For simplicity, in subsequent calculations we use  $n_i = 10^{10} / \text{cm}^3$  as the room temperature value of  $n_i$  for silicon.  $\blacklozenge$

The density of silicon atoms in the crystal lattice is approximately  $5 \times 10^{23} / \text{cm}^3$ . We see from Example 2.1 that only one bond in approximately  $10^{13}$  is broken at room temperature.

A second charge carrier is actually formed when the covalent bond in Fig. 2.3 is broken. As an electron, which has charge  $-q$  equal to  $-1.602 \times 10^{-19} \text{ C}$ , moves away from the covalent bond, it leaves behind a vacancy in the bond structure in the vicinity of its parent silicon atom. The vacancy is left with an effective charge of  $+q$ . An electron from an adjacent bond can fill this vacancy, creating a new vacancy in another position. This process allows the vacancy to move through the crystal. The moving vacancy behaves just

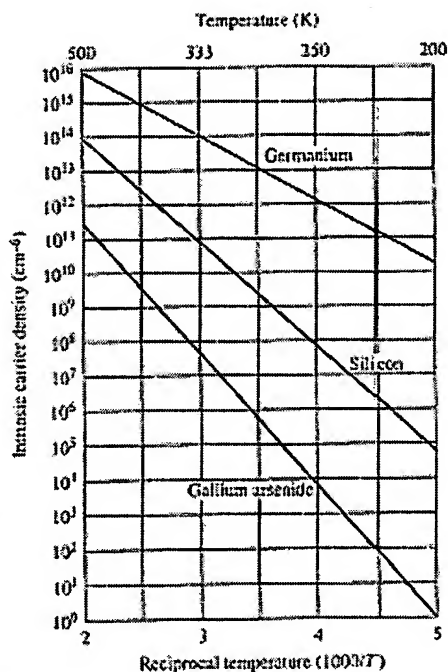


Figure 2.4 Intrinsic carrier density versus temperature from Eq. (2.2), using  $B = 1.08 \times 10^{21} \text{ K}^{-3} \cdot \text{cm}^{-6}$  for Ge,  $B = 2.31 \times 10^{20} \text{ K}^{-3} \cdot \text{cm}^{-6}$  for Si, and  $B = 1.27 \times 10^{19} \text{ K}^{-3} \cdot \text{cm}^{-6}$  for GaAs.

as a particle with charge  $+q$  and is called a hole. Hole density is represented by the symbol  $p$  (holes/cm<sup>3</sup>).

As described above, two charged particles are created for each bond that is broken: one electron and one hole. For intrinsic silicon,

$$n = n_i = p \quad (2.3)$$

and the product of the electron and hole concentrations is

$$pn = n_i^2 \quad (2.4)$$

The  $pn$  product is given by Eq. (2.4) whenever a semiconductor is in thermal equilibrium. (This very important result is used later.) In thermal equilibrium, material properties are dependent only on the temperature  $T$ , with no other form of stimulus applied. Equation (2.4) does not apply to semiconductors operating in the presence of an external stimulus such as an applied voltage or current or an optical excitation.

**EXERCISE:** Calculate the intrinsic carrier density in silicon at 50 K and 325 K. On the average, what is the length of one side of the cube of silicon that is needed to find one electron and one hole at  $T = 50 \text{ K}$ ?

**ANSWERS:**  $4.34 \times 10^{-39} \text{ cm}^{-3}$ ;  $4.01 \times 10^{10} \text{ cm}^{-3}$ ;  $6.13 \times 10^{10} \text{ m}$

## 2.4 MOBILITY

As discussed earlier, charged particles move in response to an applied electric field. This movement is termed drift, and the resulting current flow is known as drift current. Positive

$e^-$   
hole velocities

charges drift in the same direction as the electric field, whereas negative charges drift in a direction opposed to the electric field. Carrier drift velocity  $v$  (cm/s) is proportional to the electric field  $E$  (V/cm); the constant of proportionality is called the mobility  $\mu$ :

$$v_n = -\mu_n E \quad \text{and} \quad v_p = \mu_p E \quad (2.5)$$

where  $v_n$  = velocity of electrons (cm/s)

$v_p$  = velocity of holes (cm/s)

$\mu_n$  = electron mobility,  $1350 \text{ cm}^2/\text{V} \cdot \text{s}$  in intrinsic Si

$\mu_p$  = hole mobility,  $500 \text{ cm}^2/\text{V} \cdot \text{s}$  in intrinsic Si

Conceptually, holes are localized to move through the covalent bond structure, but electrons are free to move about the crystal. Thus, one might expect hole mobility to be less than electron mobility, as appears in the definitions in Eq. (2.5). Note that the relationship in Eq. (2.5) breaks down at high fields in all semiconductors because the velocity of carriers reaches a limit called the saturated drift velocity  $v_{sat}$ . In silicon,  $v_{sat}$  is approximately  $10^7$  cm/s for electric fields exceeding  $3 \times 10^4$  V/cm.

**EXERCISE:** Calculate the velocity of a hole in an electric field of 10 V/cm. What is the electron velocity in an electric field of 1000 V/cm? The voltage across a resistor is 1 V, and the length of the resistor is 2  $\mu\text{m}$ . What is the electric field in the resistor?

**ANSWERS:**  $5.00 \times 10^3$  cm/s;  $1.35 \times 10^6$  cm/s;  $5.00 \times 10^3$  V/cm.

## 2.5 RESISTIVITY OF INTRINSIC SILICON

We are now in a position to calculate the electron and hole drift current densities  $j_n^{drift}$  and  $j_p^{drift}$ . For simplicity, we assume a one-dimensional current and avoid the vector notation of Eq. (2.1):

$e^-$   
hole drift  
current  
densities

$$\begin{aligned} j_n^{drift} &= Q_n v_n = (-qn)(-\mu_n E) = qn\mu_n E \quad \text{A/cm}^2 \\ j_p^{drift} &= Q_p v_p = (+qp)(+\mu_p E) = qp\mu_p E \quad \text{A/cm}^2 \end{aligned} \quad (2.6)$$

in which  $Q_n = (-qn)$  and  $Q_p = (+qp)$  represent the charge densities ( $\text{C/cm}^3$ ) of electrons and holes, respectively. The total drift current density is then given by

$$j_T^{drift} = j_n + j_p = q(n\mu_n + p\mu_p)E = \sigma E \quad (2.7)$$

This equation defines  $\sigma$ , the electrical conductivity:

$$\sigma = q(n\mu_n + p\mu_p) \quad (\Omega \cdot \text{cm})^{-1} \quad (2.8)$$

For intrinsic silicon, the charge density of electrons is given by  $Q_n = -qn_i$ , whereas the charge density for holes is  $Q_p = +qn_i$ . The values of the mobilities in intrinsic silicon were given in Eq. (2.5), and

$$\begin{aligned} \sigma &= (1.60 \times 10^{-19})[(10^{10})(1350) + (10^{10})(500)] \quad (\text{C})(\text{cm}^{-3})(\text{cm}^2/\text{V} \cdot \text{s}) \\ &= 2.96 \times 10^{-6} (\Omega \cdot \text{cm})^{-1} \end{aligned}$$

The resistivity  $\rho$  is equal to the reciprocal of the conductivity, so for intrinsic silicon

$$\rho = \frac{1}{\sigma} = 3.38 \times 10^5 \Omega \cdot \text{cm} \quad (2.9)$$

From Table 2.1, we see that intrinsic silicon can be characterized as an insulator, albeit near the low end of the insulator resistivity range.